# NEW RESULTS ON THE $\mu^+ \rightarrow e^+ \gamma$ DECAY FROM THE MEG EXPERIMENT

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# Outline

- Motivations
- The event signature and backgrounds
- The MEG experiment
- The 2009 detector performances
- The new results

# Motivations

- Very sensitive tool to investigate physics beyond Standard Model

- Experimental evidence of LVF in neutral sector from neutrino oscillations

$$\mathcal{P}_{\nu_l \to \nu_{l'}} = \quad |\langle \nu_{l'} | \nu_l \rangle|^2 = \left| \sum_i V_{li} V^*_{l'i} e^{-i(m_i^2/2E_i)/L} \right|^2 \neq 0$$

- No yet observation of LVF in charged sector, but new physics predicts observable B.R.

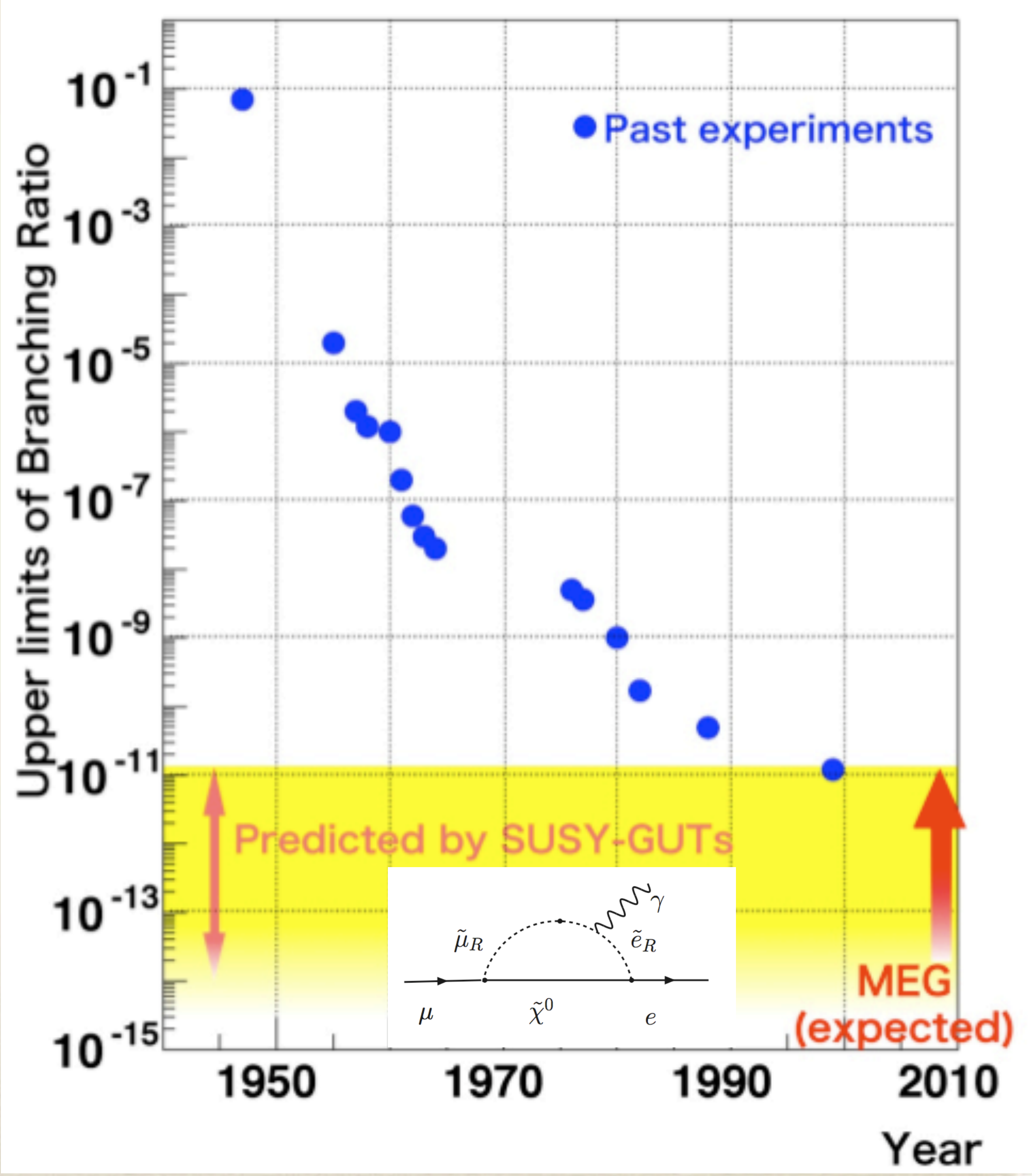
$$10^{-14} < B(\mu^+ \to e^+ \gamma) < 10^{-11}$$

- The best upper limit (MEGA experiment)

$$B.R. \leq 1.2 \times 10^{-11} @ 90\% C.L.$$

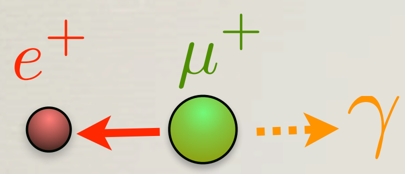
- The MEG sensitivity (goal)

$$B.R. \leq few \times 10^{-13} @ 90\% C.L.$$



# Event signature and background

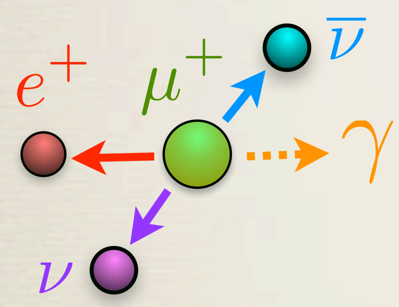
- Signature of the muon decay at rest




Positron and gamma
in timing coincidence,
moving collinearly back-to-back,
with their energies equal to ~ 52.8 MeV

$B \sim 10^{-13}$

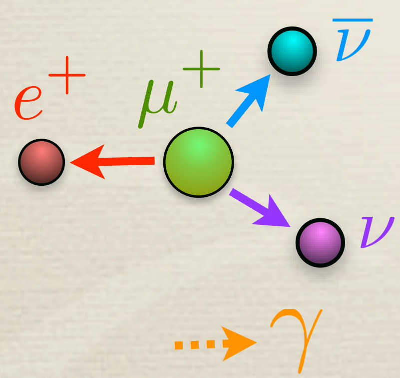
- Correlated background




Positron and gamma
in opposite directions,
two neutrinos with a small amount of energy

$B \sim 10^{-15}$

- Accidental background

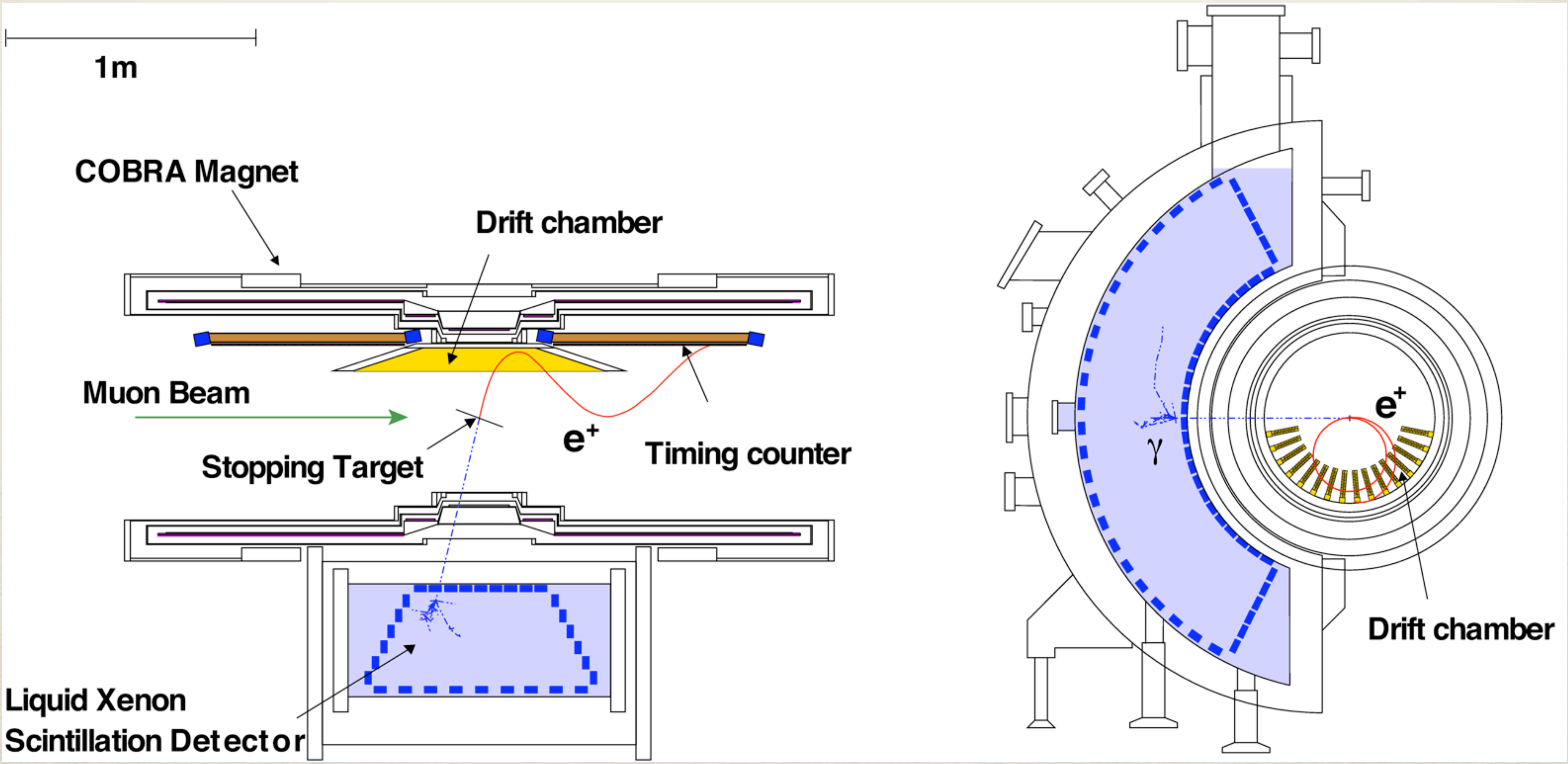



Timing coincidence between
Michel positron and gamma from
radiative muon decay or positron
annihilation in flight

$B \sim 10^{-14}$

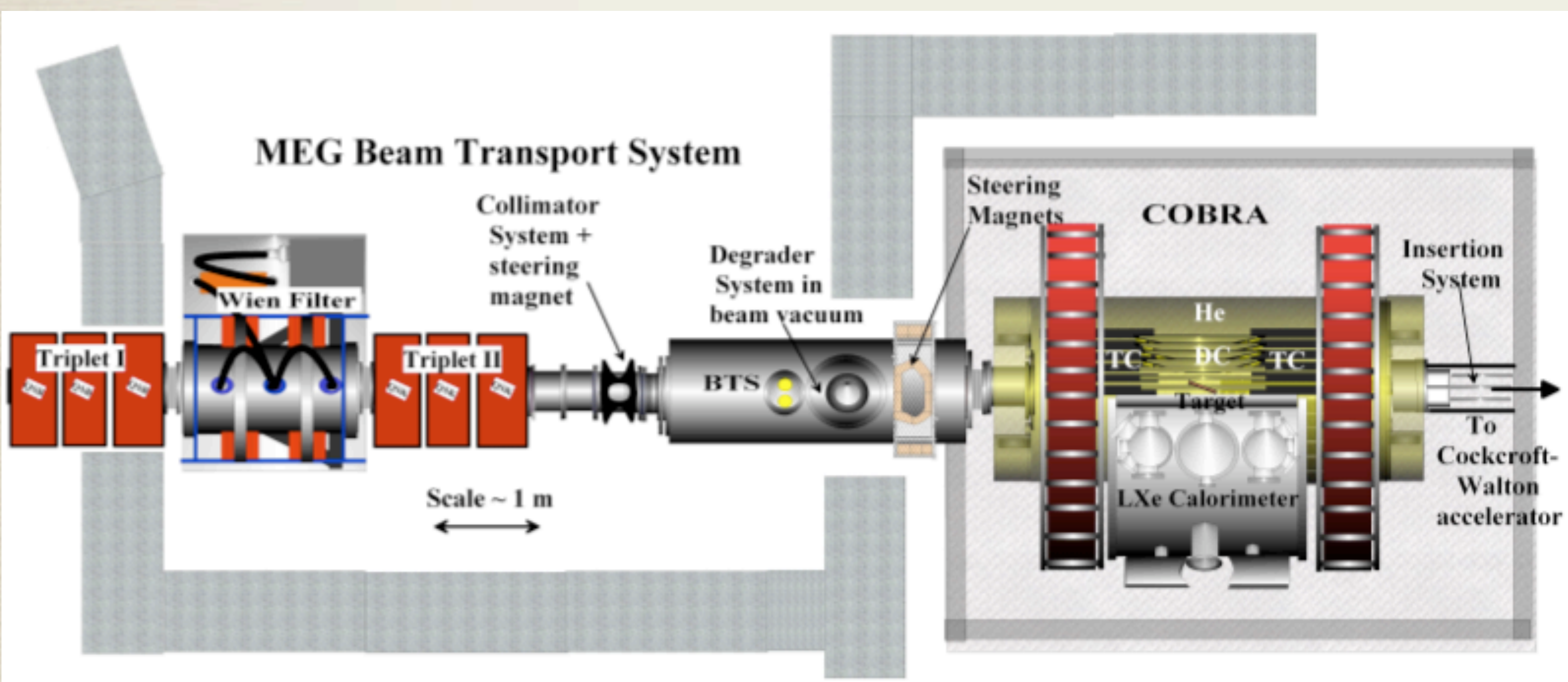
# The experimental set-up

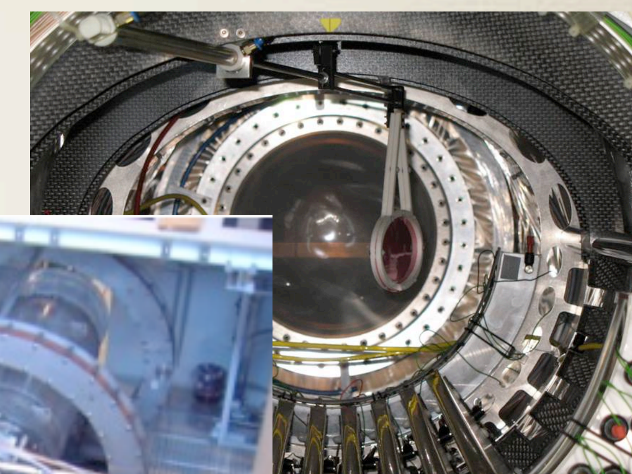
- The most intense DC Muon Beam
- High energy and time Photon detection resolutions
  - LXe calorimeter (energy,direction and time)
- Very precise energy and time Positron detection resolutions
  - COBRA magnet + Drift chamber (momentum and direction)
  - Timing counter (time)
- High efficiency event selection and high frequency signal digitization
  - Trigger and DAQ system
- Complementary calibration and monitoring methods

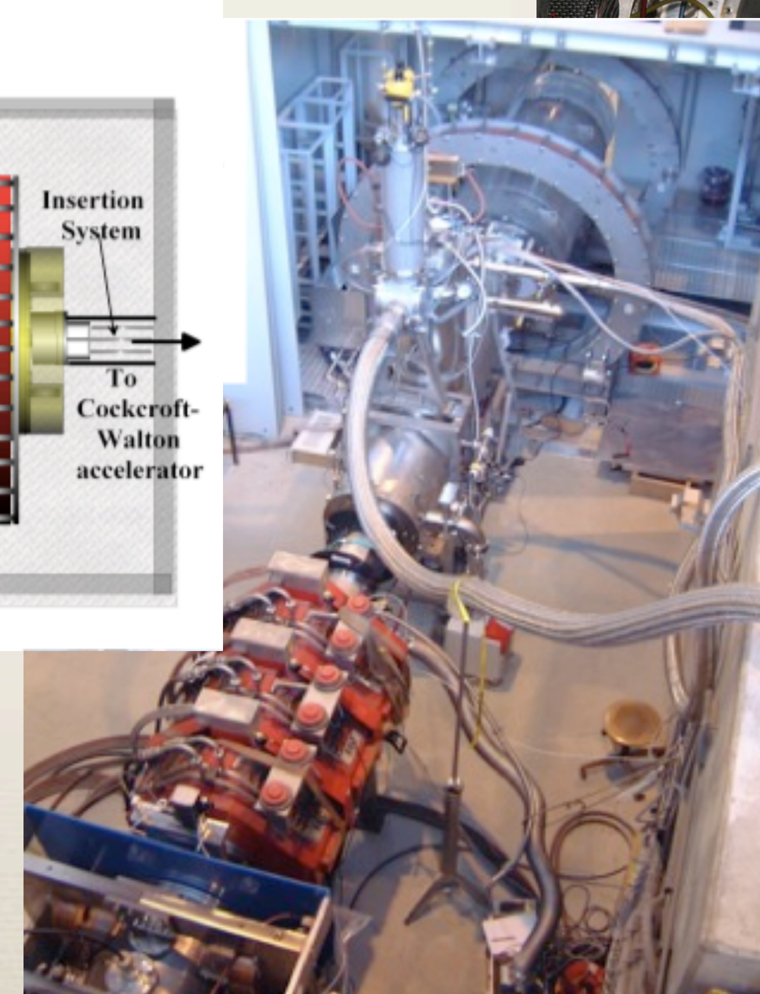


# Surface Muon beam

- Pure muon beam at low momentum
  - small straggling and good identification of the muon decay region
    - Reducing contaminants (beam particles other than muons)
    - Reducing the beam momentum to stop muons in a thin target

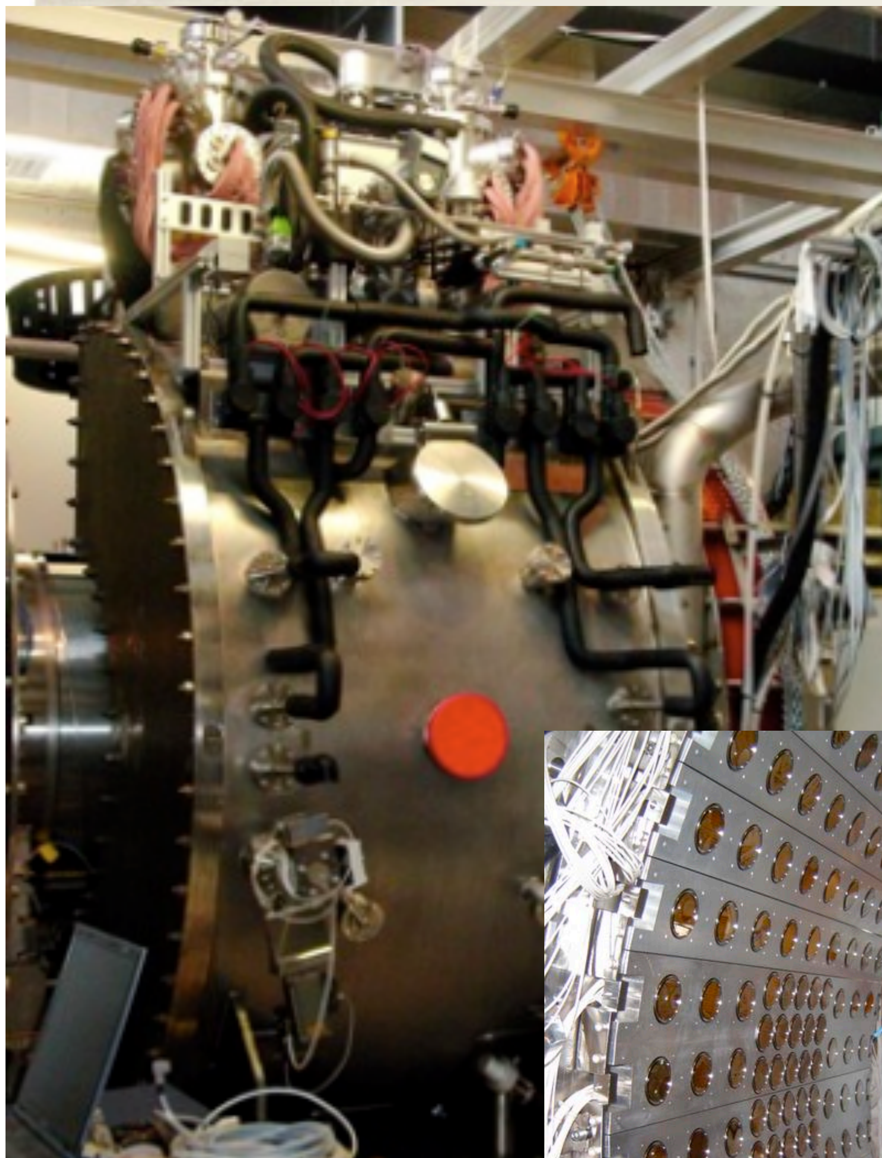


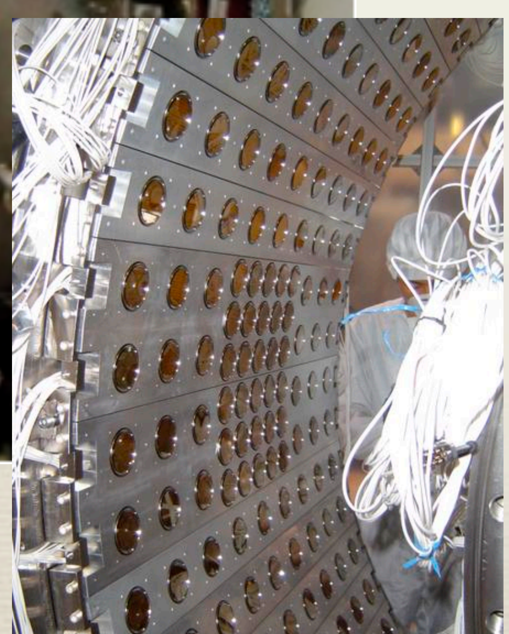



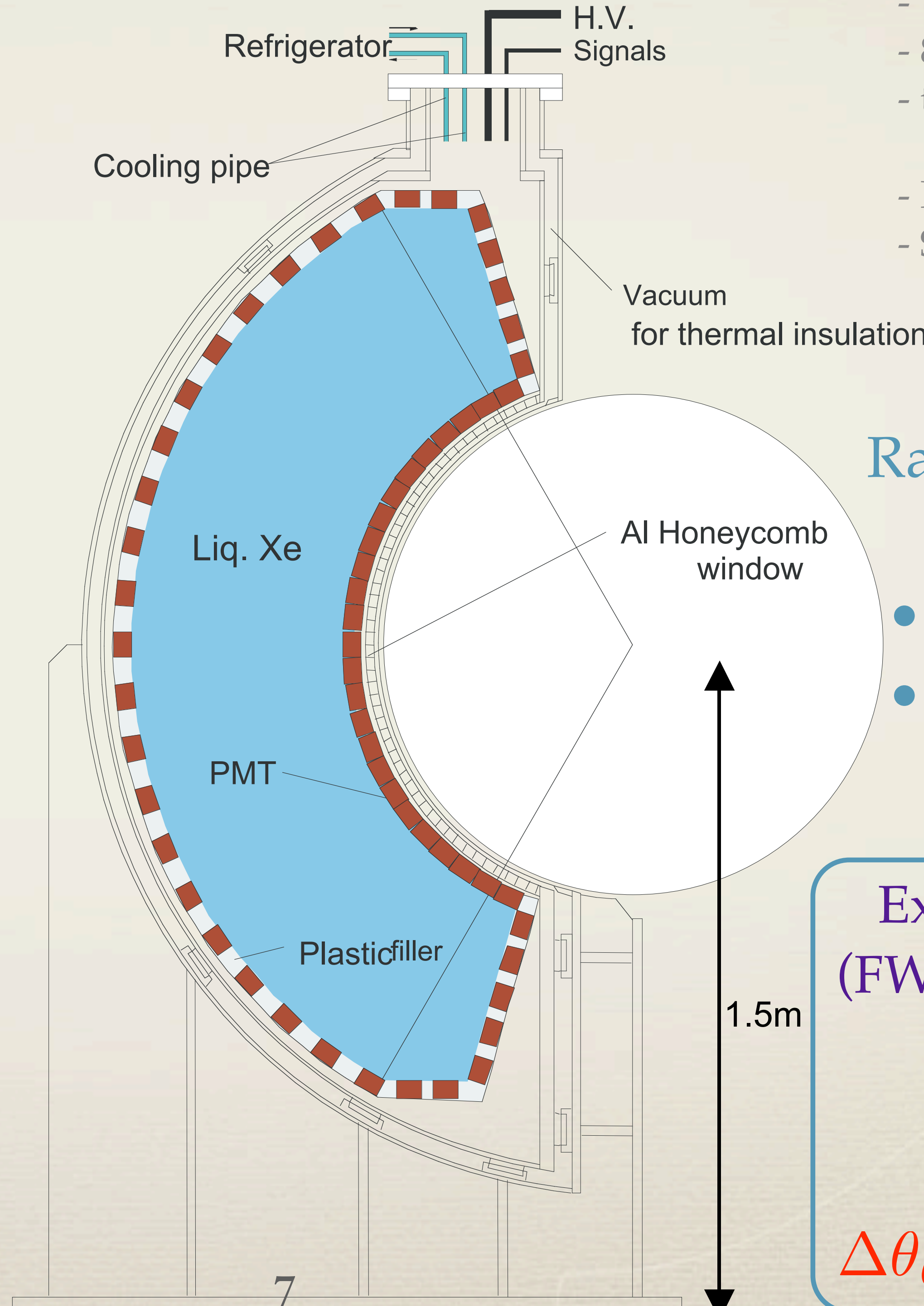


# The LXe calorimeter

- The larger homogeneous calorimeter using only scintillation light
  - very good resolutions for photon energy, direction and time measurements








- Volume: 0.9 $m^3$ LXe
- 846 PMTs immersed in LXe
- thin entrance wall (honeycombe structure)
- Photocathodic coverage 40%
- Solid angle coverage 10%of 4π

Rapid and high light yield scintillator

- τ = 4, 22 and 45 ns
- ~ 40000 ph/MeV

Expected Resolutions
(FWHM, MC simulation)
@ 52.8 MeV

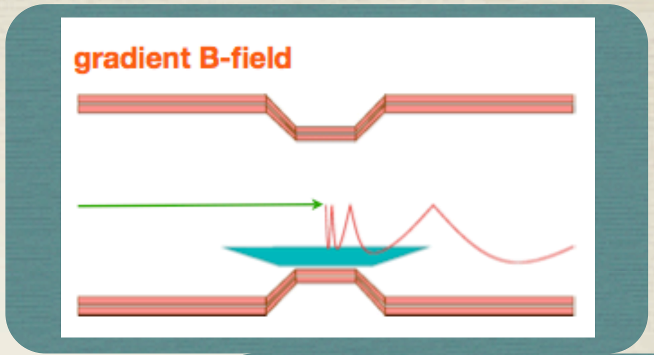
$\Delta E_\gamma / E_\gamma = 4.5\%$

$\Delta t_\gamma = 115 ps$

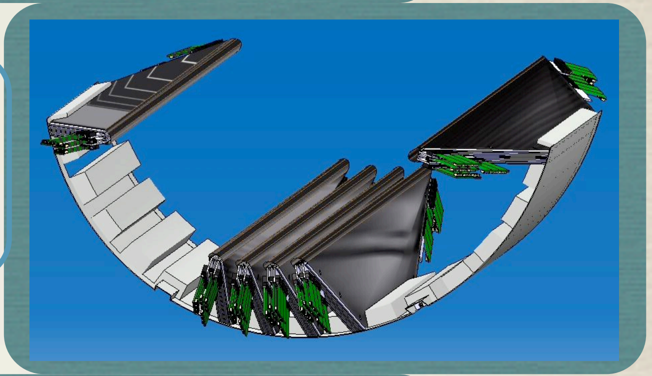
$\Delta\theta_{\theta,\phi} \approx 16 - 18 mrad$

# The positron Spectrometer

- Superconducting magnet
  - Gradient B-field
    - low momentum e+ swept away
    - constant projected radius

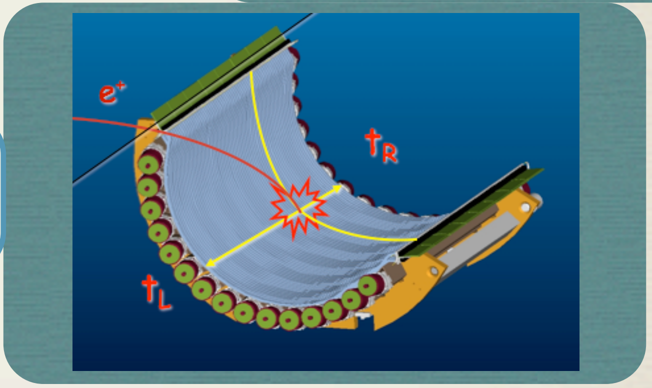



$\Delta p_{e^+}/p_{e^+} = 0.7 - 0.9\%$ (*)
$\Delta \theta_{e^+} = 9 - 12 mrad$ (*)

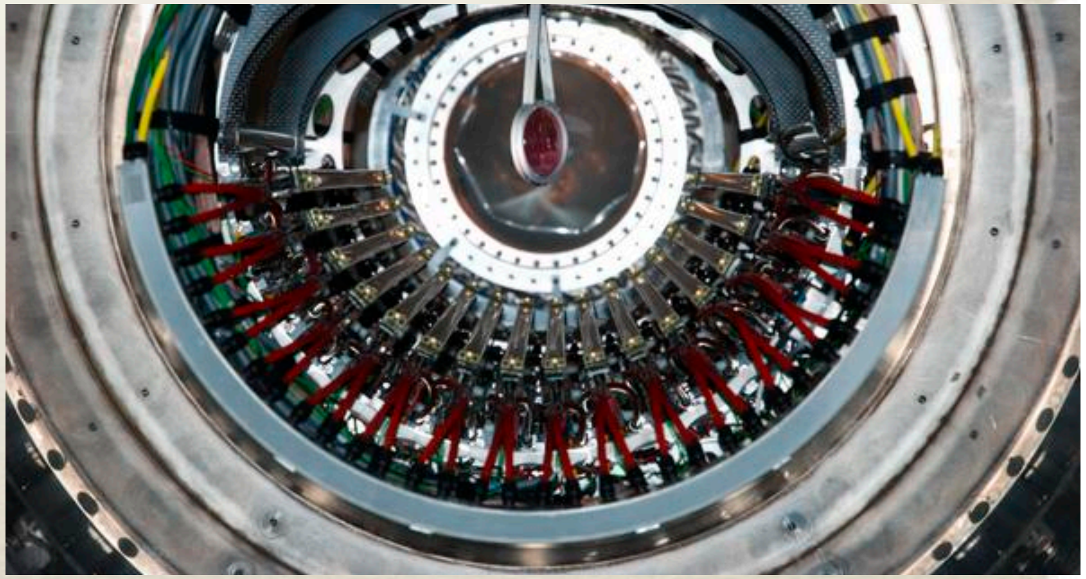


- Drift chambers array
  - 16 sectors, 2 dch each, with staggered wire layers
    - good e+ momentum and direction measurements
    - good time resolution (track recostruction)

$\Delta t = 100 ps$ (*)




- Scintillator bars and optical fibers
  - Two sectors of 15 bars coupled of PMTs
    - excellent time resolution
    - fast estimate of e+ emission angle
  - 256 fibers coupled to APDs
    - fast determination of the e+ impact point

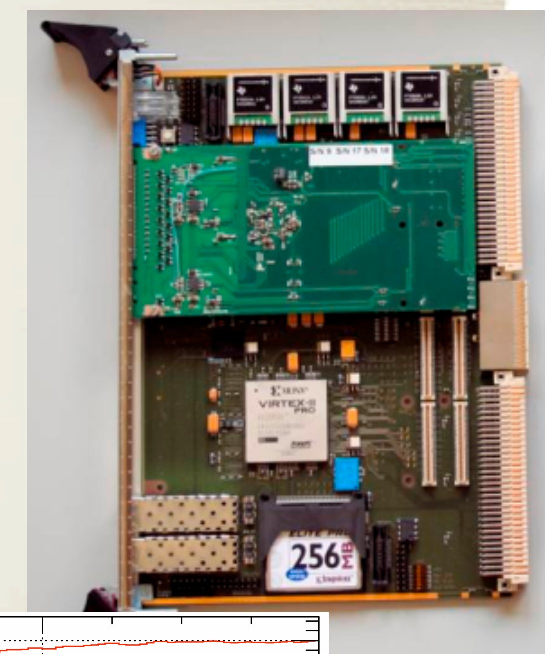


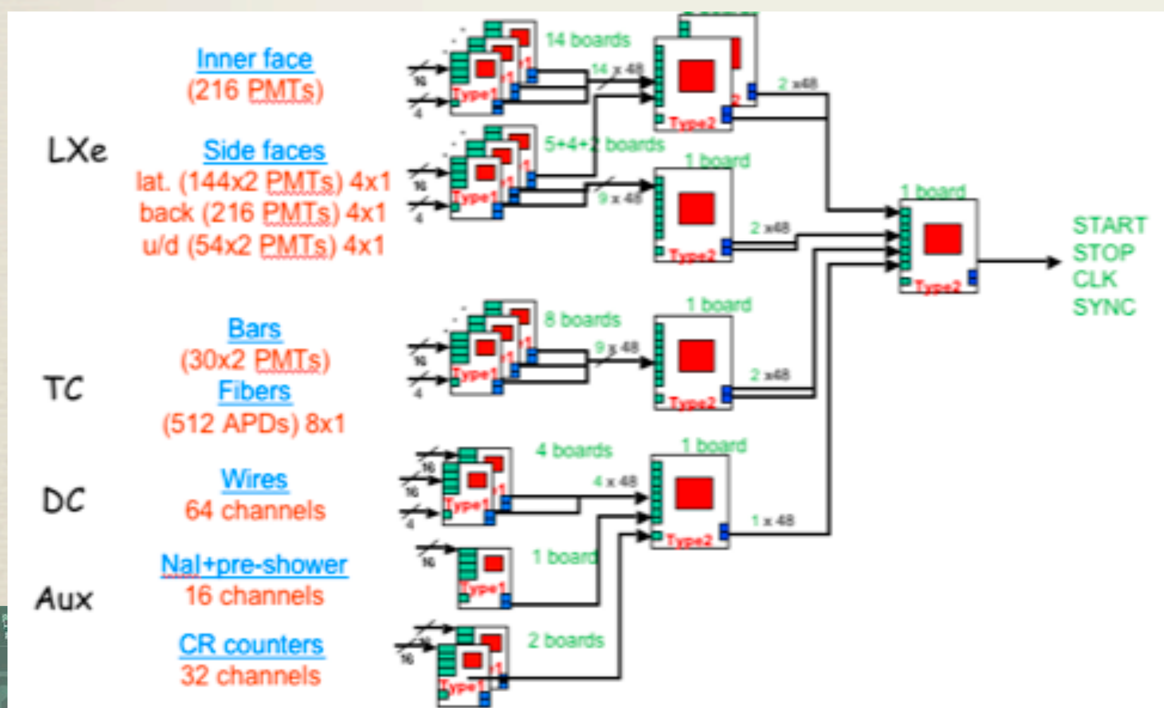


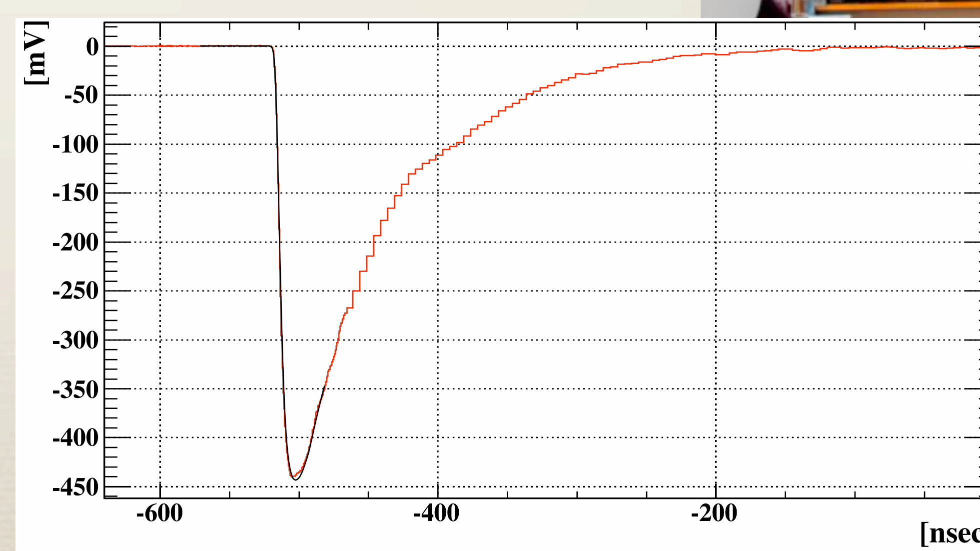
(*) Expected Resolutions (FWHM, MC simulation) @ 52.8 MeV

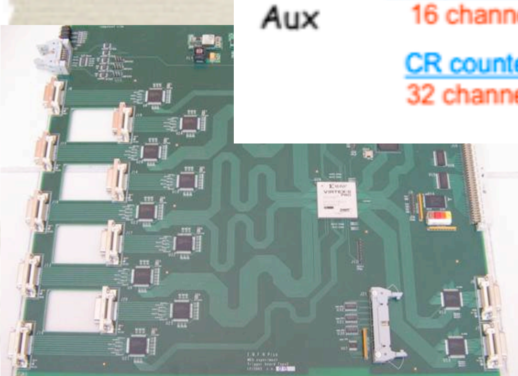
# Trigger and DAQ

- Flexible and efficient trigger system, to select the candidate events, using fast detectors only
  - FADC digitization at 100 MHz
  - online selection algorithms implemented into FPGAs
- Domino Ring Sampler (DRS) chip for excellent pile-up rejection with a full waveform digitization
  - all 1000 PMTs signals (LXe and TC) digitize at 1.6 GHz
  - all 3000 DC channels (anodes and cathodes) digitize at 800 MHz



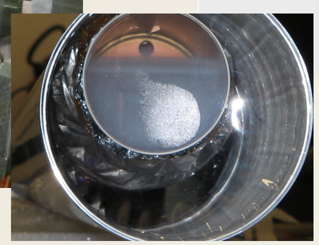
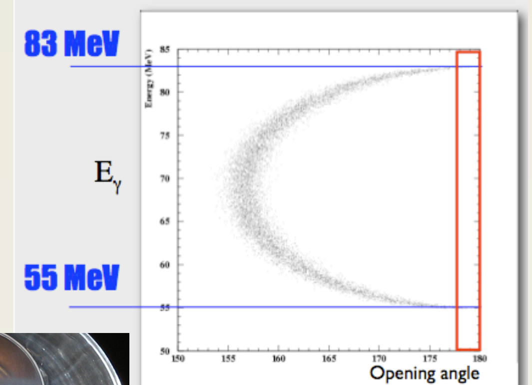


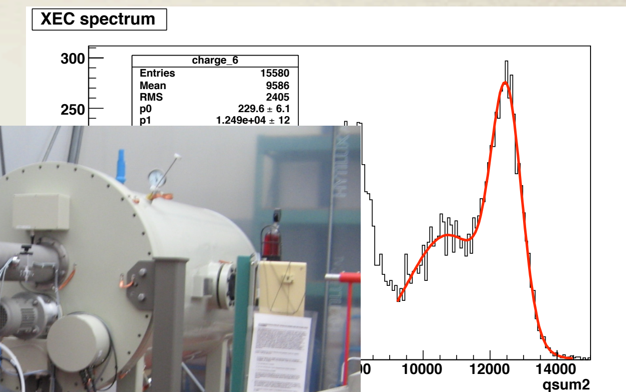



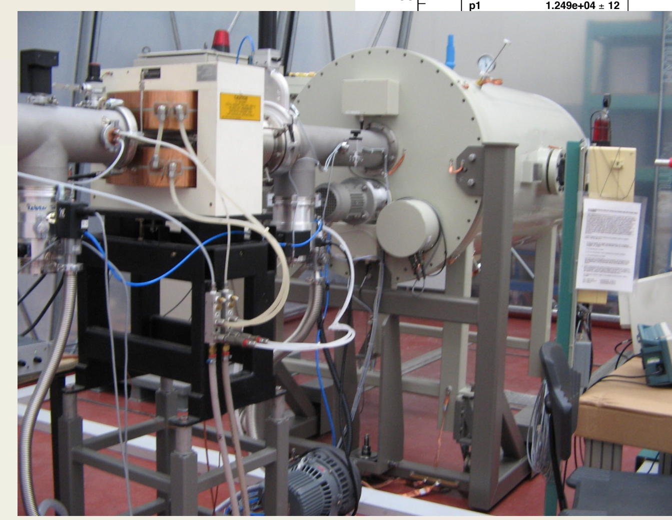



# Calibration methods

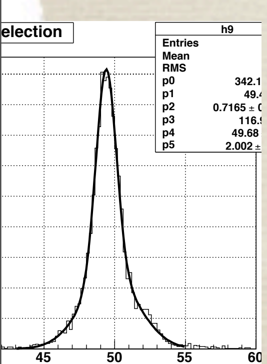
- Several complementary and redundant methods to calibrate and monitor all detectors
  - the ONLY way to ensure that required performances are reached and maintained during the time

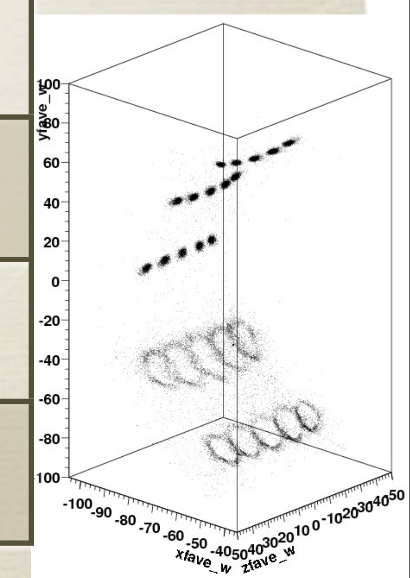
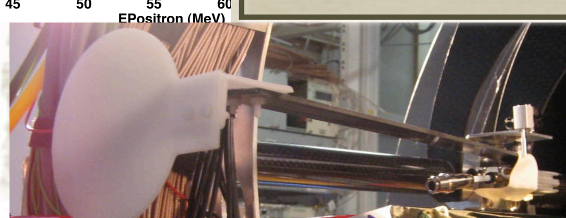
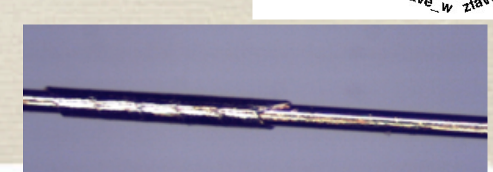








| Physical process | | Particle/energy (MeV) | Frequence |
|---|---|---|---|
| CEX | $p(\pi^-,\pi^0)n$<br>$\pi^0 \rightarrow \gamma\gamma$<br>$\pi^0 \rightarrow \gamma e^+ e^-$ | e/γ = 55, 83 | year -month |
| C-W accelerator | ${}_3^7Li(p,\gamma)_4^8Be$<br>${}_5^{11}B(p,\gamma)_6^{12}C$ | γ = 4.4, 11.7, 17.6 | week |
| Radioactive sources | Am-Am/Be | γ = 4.4; α = 5.4 | day |
| $e^+$ Mott scattering | $p(e^+,e^+)p$ | e = 50, 55, 60 | year -month |



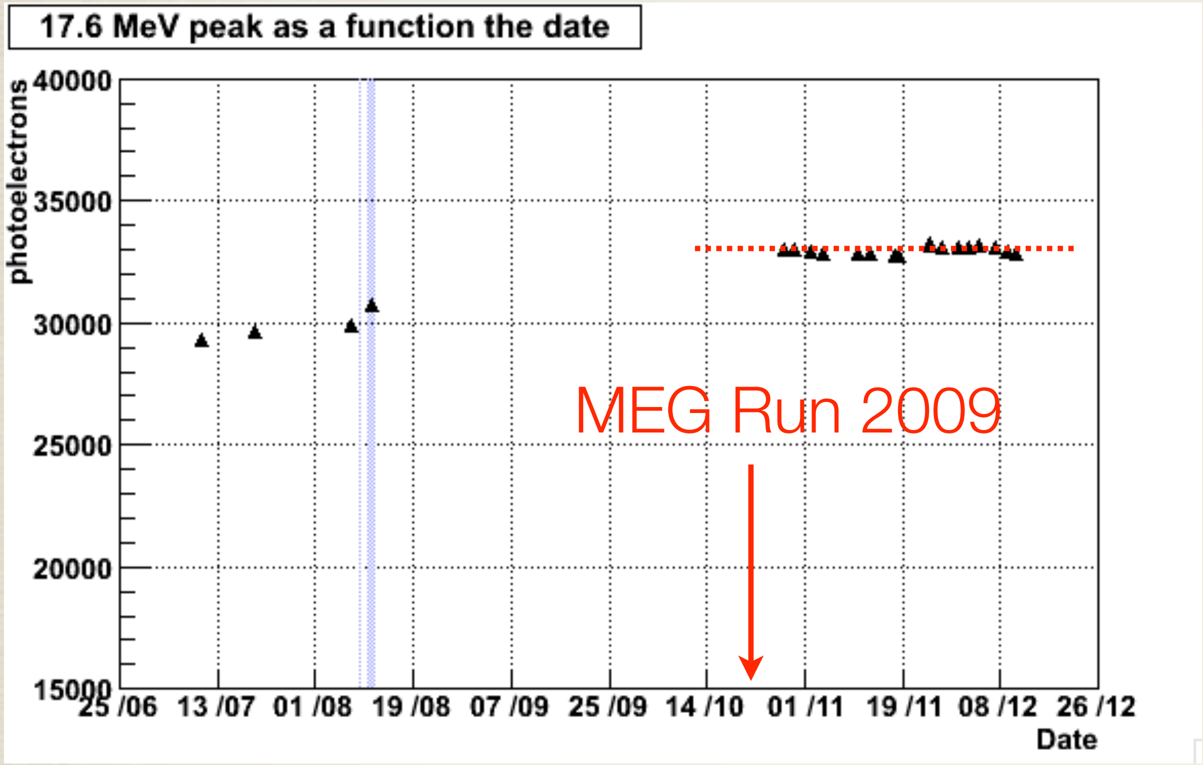
# Detector Performances

| Variable (in sigma) | 2008 | 2009 |
|---|---|---|
| Gamma Energy (%) | 2.0 (w>2cm ) | ← |
| Gamma Timing (psec) | 80 | > 67 |
| Gamma Position (mm) | 5 (u,v) - 6 (w) | ← |
| Gamma Efficiency (%) | 63 | 58 |
| Positron Momentum (%) | 1.6 | 0.74 (core) |
| Positron Timing (psec) | <125 | ← |
| Positron Angle (mrad) | 10 (φ) - 18 (ϑ) | 7.4 (φ) - 11.2 (ϑ) |
| Positron Efficiency (%) | 14 | 40 |
| Gamma-Positron Timing (psec) | 148 | 142 (core) |
| Muon decay point (mm) | 3.2 (R) - 4.5 (Z) | 2.3 (R) - 2.8 (Z) |
| Trigger efficiency (%) | 66 | 84 |
| DAQ time/Real time (days) | 48/78 | 35/43 |
| Stopping Muon Rate ($sec^{-1}$) | $3 \times 10^{7}$ | $2.9 \times 10^{7}$ |
| Sensitivity | $1.3 \times 10^{-11}$ | - |
| B.R. upper limit | $2.8 \times 10^{-11}$ | - |

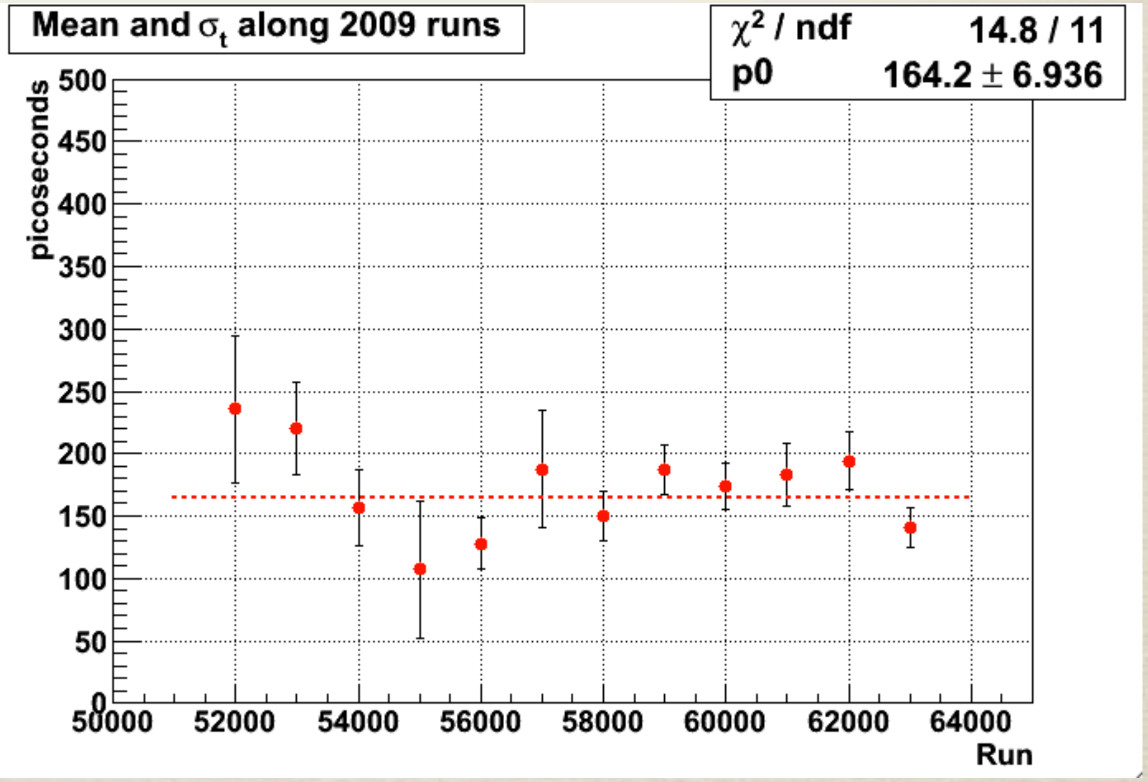
# Detector Stability

- Just some example...

Xe LY as a function of time by CW accelerator.
Stability <1% level




RMD resolution as a function of time. Average ~ 160 ps



# MEG Event selection

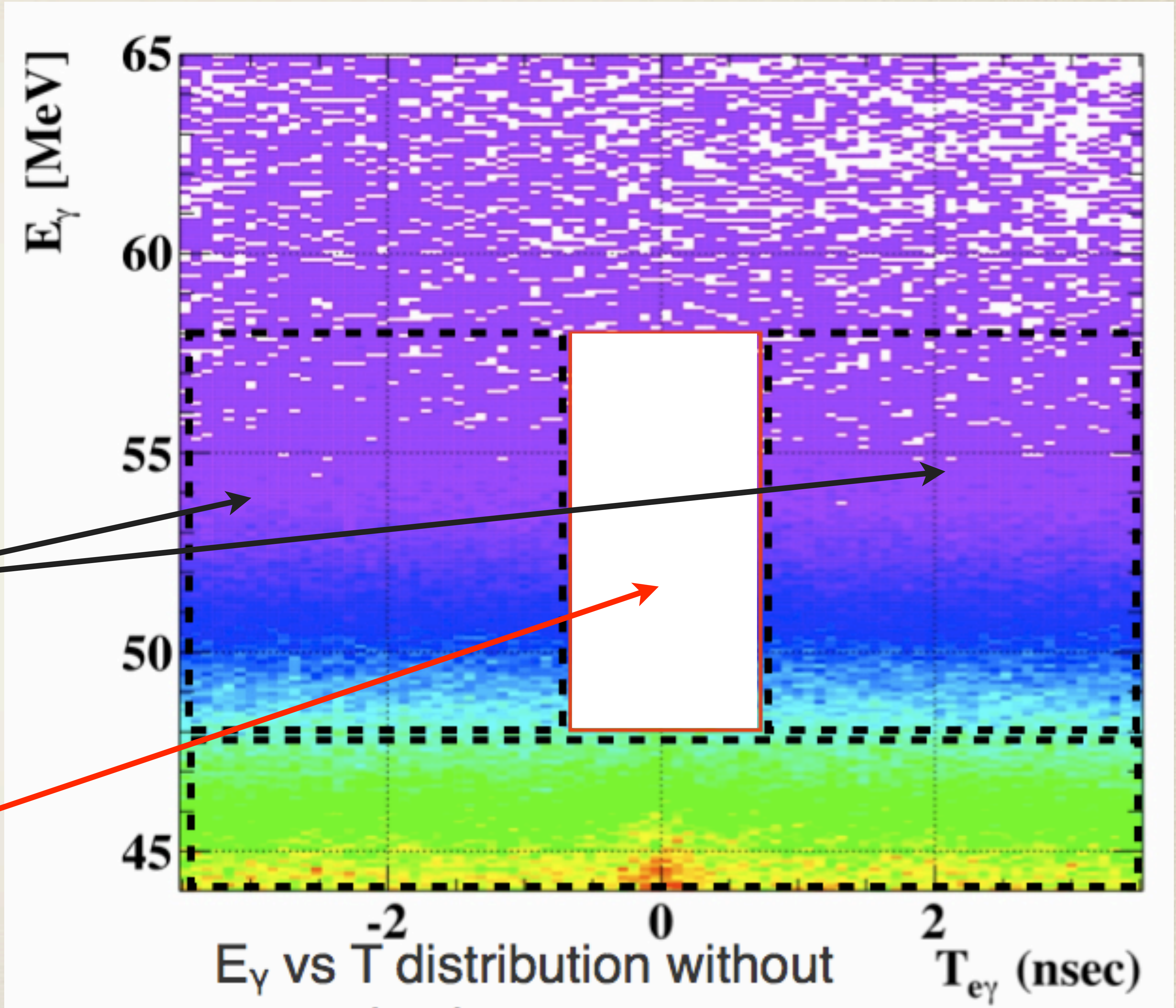
- Analysis box (~10 σ)
  - $48 < E_\gamma$ (MeV) $< 58$
  - $50 < E_e$ (MeV) $< 56$
  - $|T_{e\gamma}| < 0.7$ ns
  - $|\Phi_{e\gamma}|$ , $|\theta_{e\gamma}| < 50$ mrad

**Side-boxes**

Events used for optimizing algorithms and background studies

**Blinding box**

Events saved in separated hidden files




$E_\gamma$ vs T distribution without any selection.

# Analysis strategies

- A candidate $\mu \rightarrow e\gamma$ event is characterized by 5 kinematical variables: $E_g$, $E_e$, $t_{eg}$, $\vartheta_{eg}$, $\phi_{eg}$

- Three indipendent likelihood analyses were performed to check possible systematic effects

- Likelihood function is built in terms of Signal S, radiative Michel decay RMD and background BG number of events and their probability density function PDFs (S,R and B):

$$\mathcal{L}(N_{sig}, N_{RMD}, N_{BG}) = \frac{N^{N_{obs}} e^{-N}}{N_{obs}!} \prod_{i=1}^{N_{obs}} \left[ \frac{N_{sig}}{N} S + \frac{N_{RMD}}{N} R + \frac{N_{BG}}{N} B \right]$$

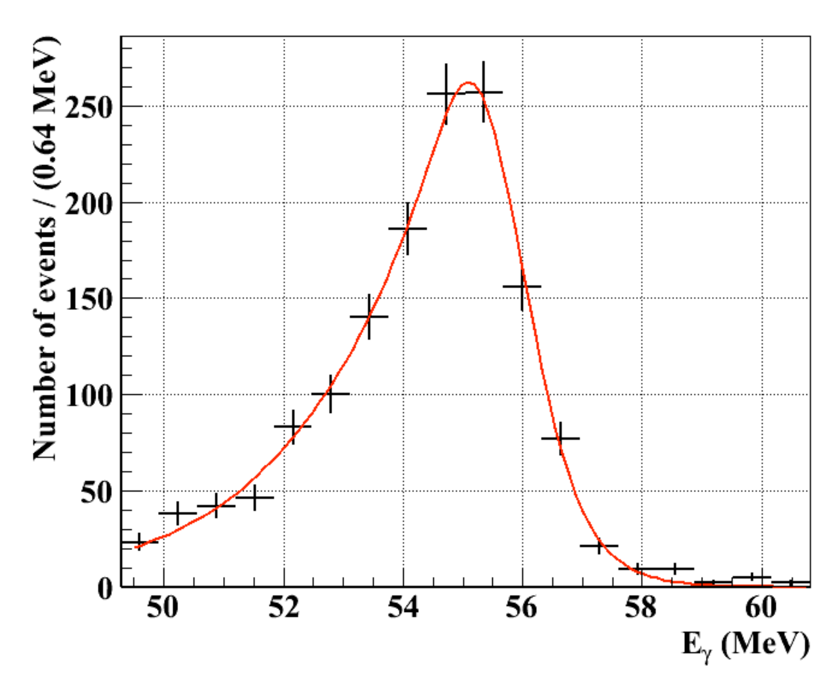
Signal PDF:
is the product of the PDFs for the 5 kinematical variables $E_g$, $E_e$, $t_{eg}$, $\vartheta_{eg}$, $\phi_{eg}$

RMD PDF:
is the product of the theoretical PDF ( correlated $E_g$, $E_e$, $\vartheta_{eg}$, $\phi_{eg}$ ) folded with detector response, and the measured $t_{eg}$ PDF (same of signal one)

BG PDF:
is the product of the background spectra of the 5 kinematical variables $E_g$, $E_e$, $t_{eg}$, $\vartheta_{eg}$, $\phi_{eg}$, precise measured in the side-bands

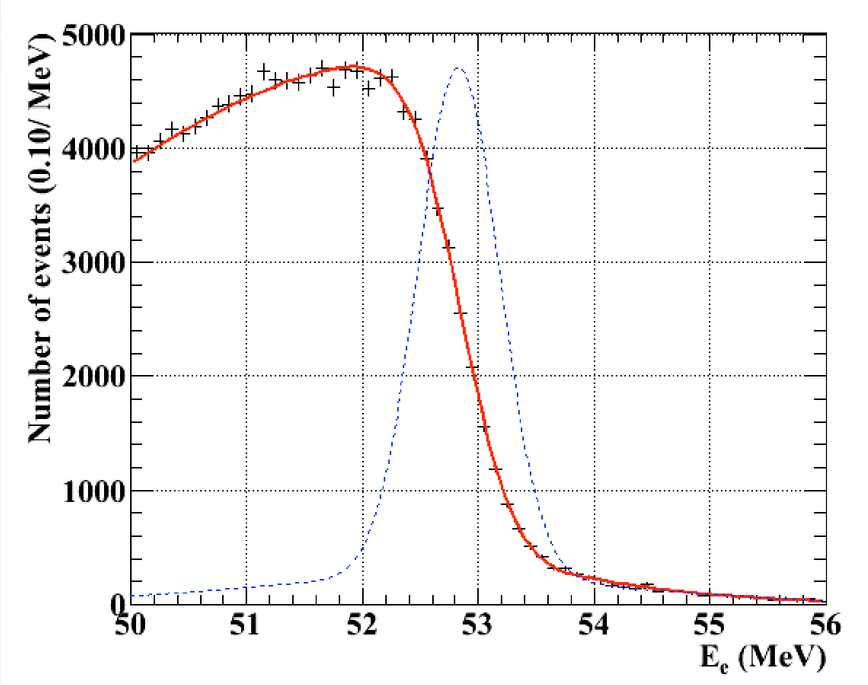
# Examples of PDFs

From $\pi^-$ CEX reaction



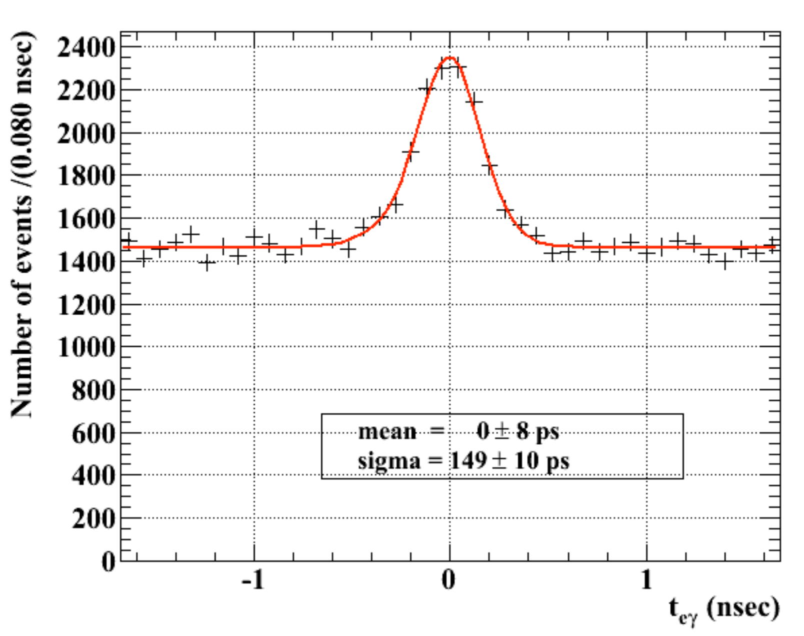

$E_\gamma$

From Michel $e^+$



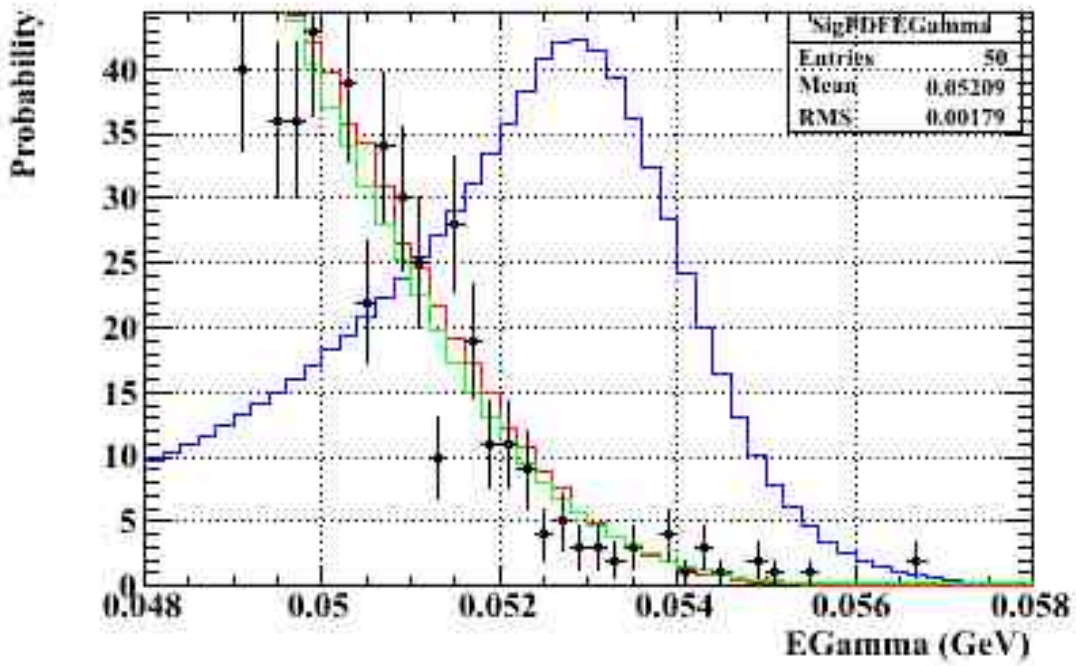

$E_{e+}$

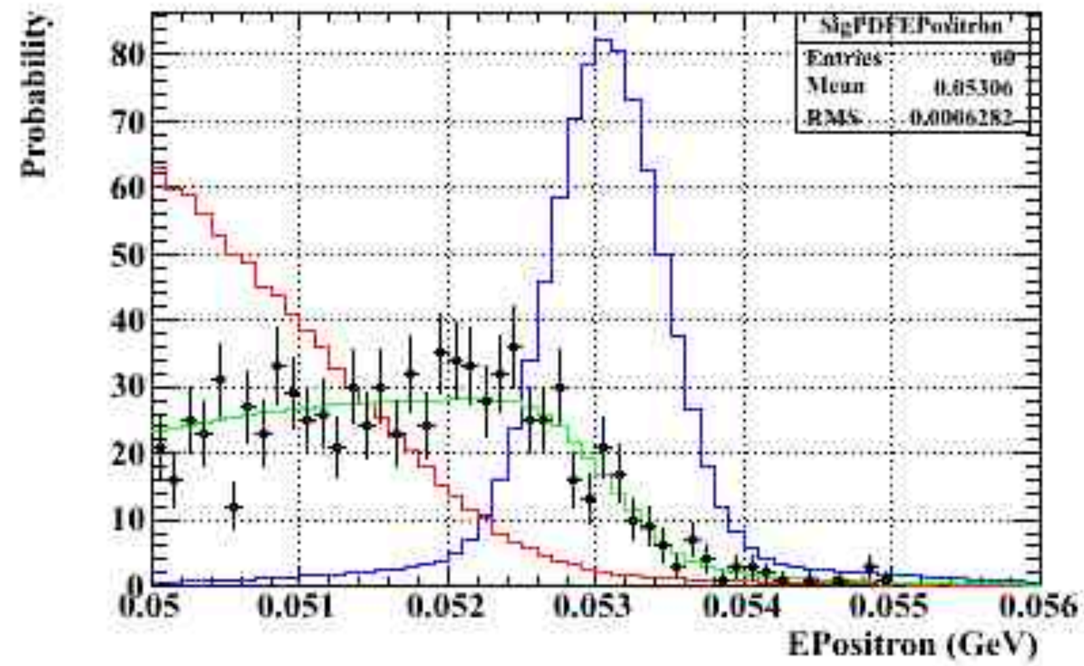
$t_{e\gamma}$

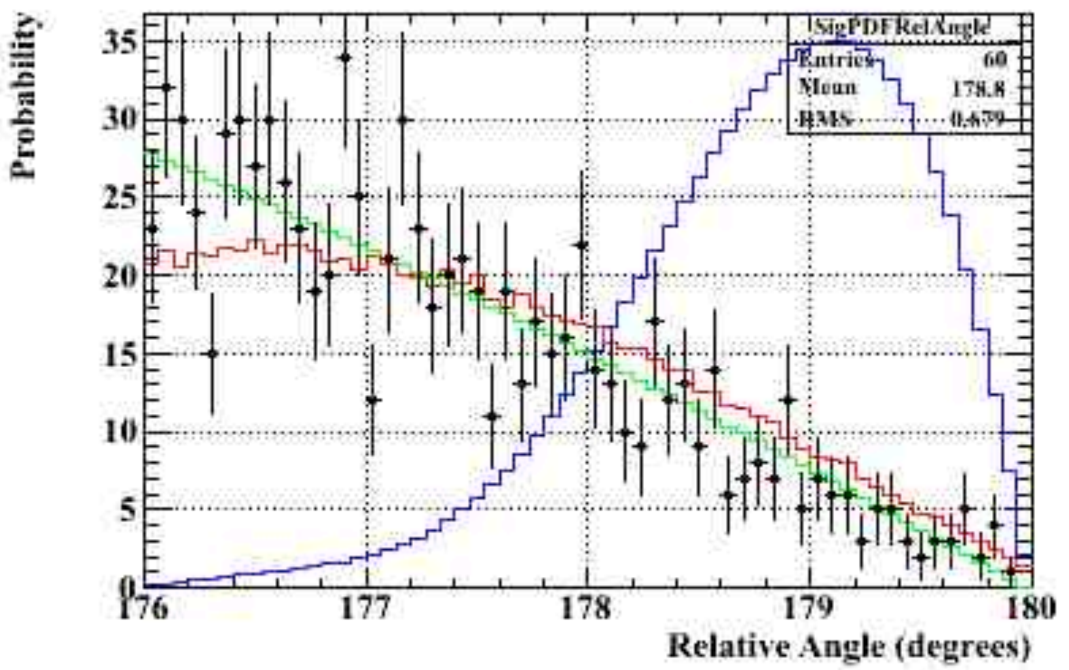



From Radiative μ decay

# Events in sideband vs PDFs



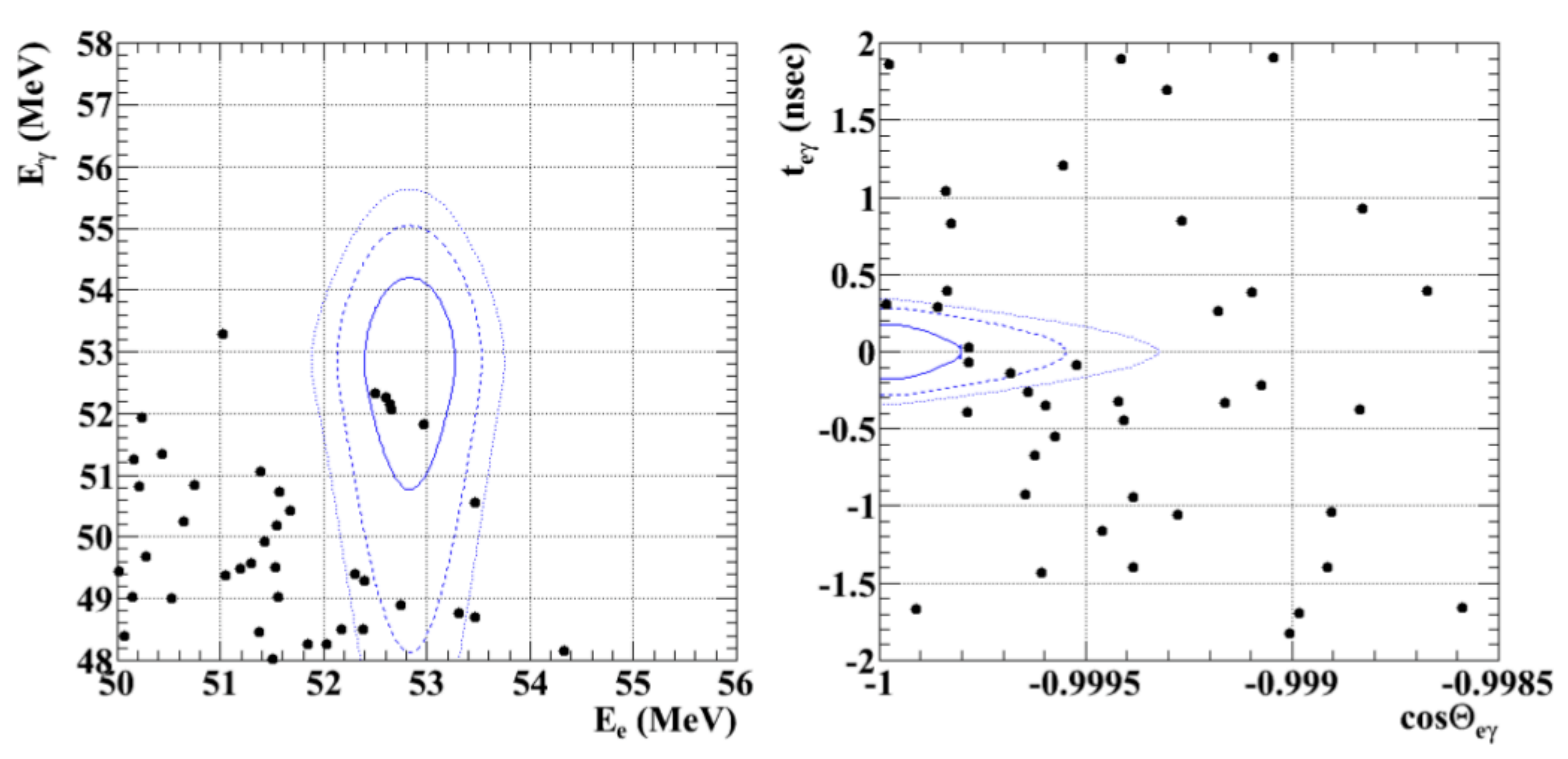




Black dots: Data
Red: RMD
Green: BCK
Blue: Signal

# Event distribution after unblinding

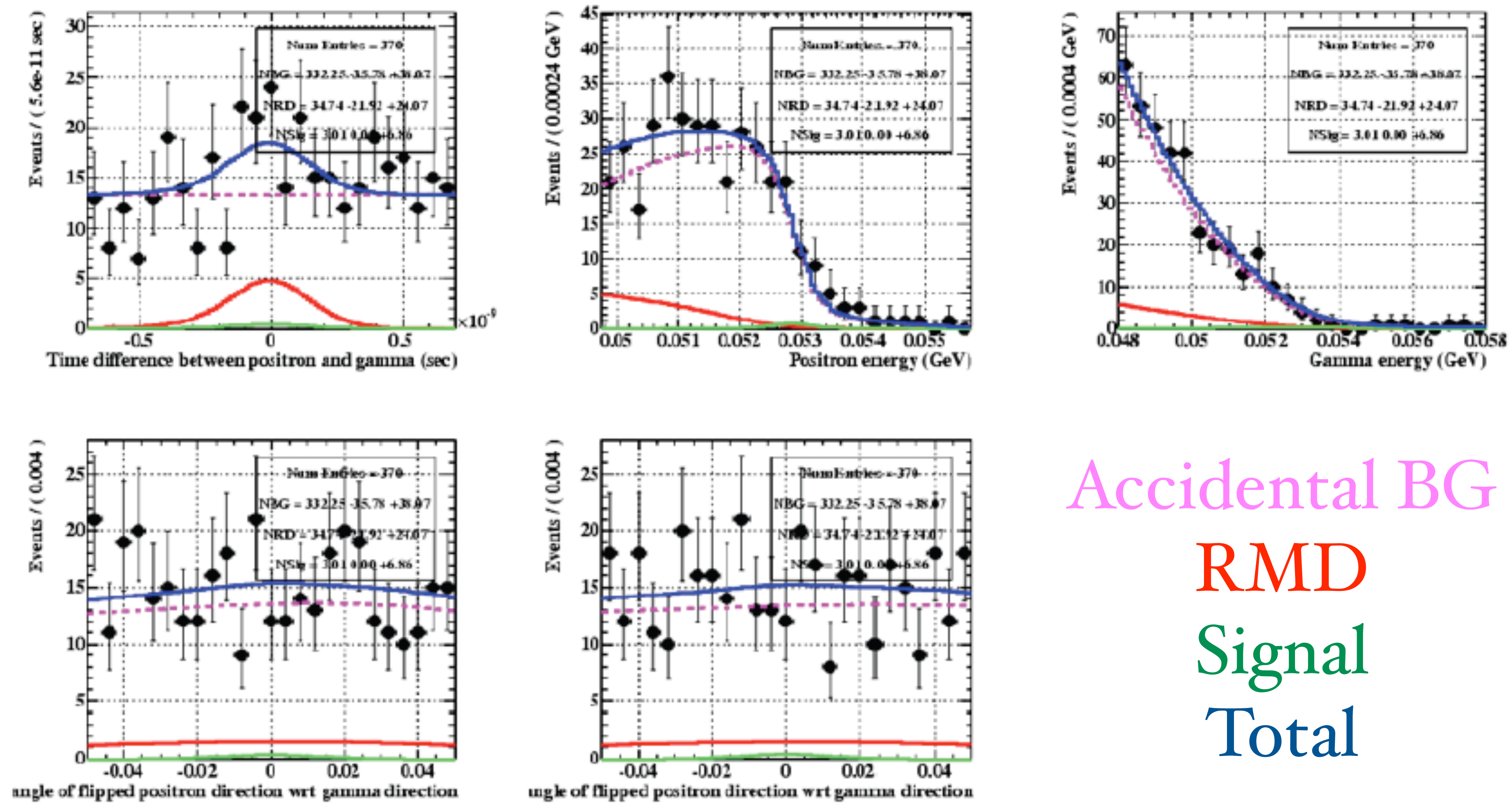
- Blue lines are at 1 (39.3%), 1.64 (74.2%) and 2 (86.5%) sigma
- For each plot cut in the other variables for roughly 90% window is applied



# Fit results

- Nsig < 14.5 @ 90% C.L.
- Nsig = 0 is in 90% confidence region
- Nsig best fit = 3

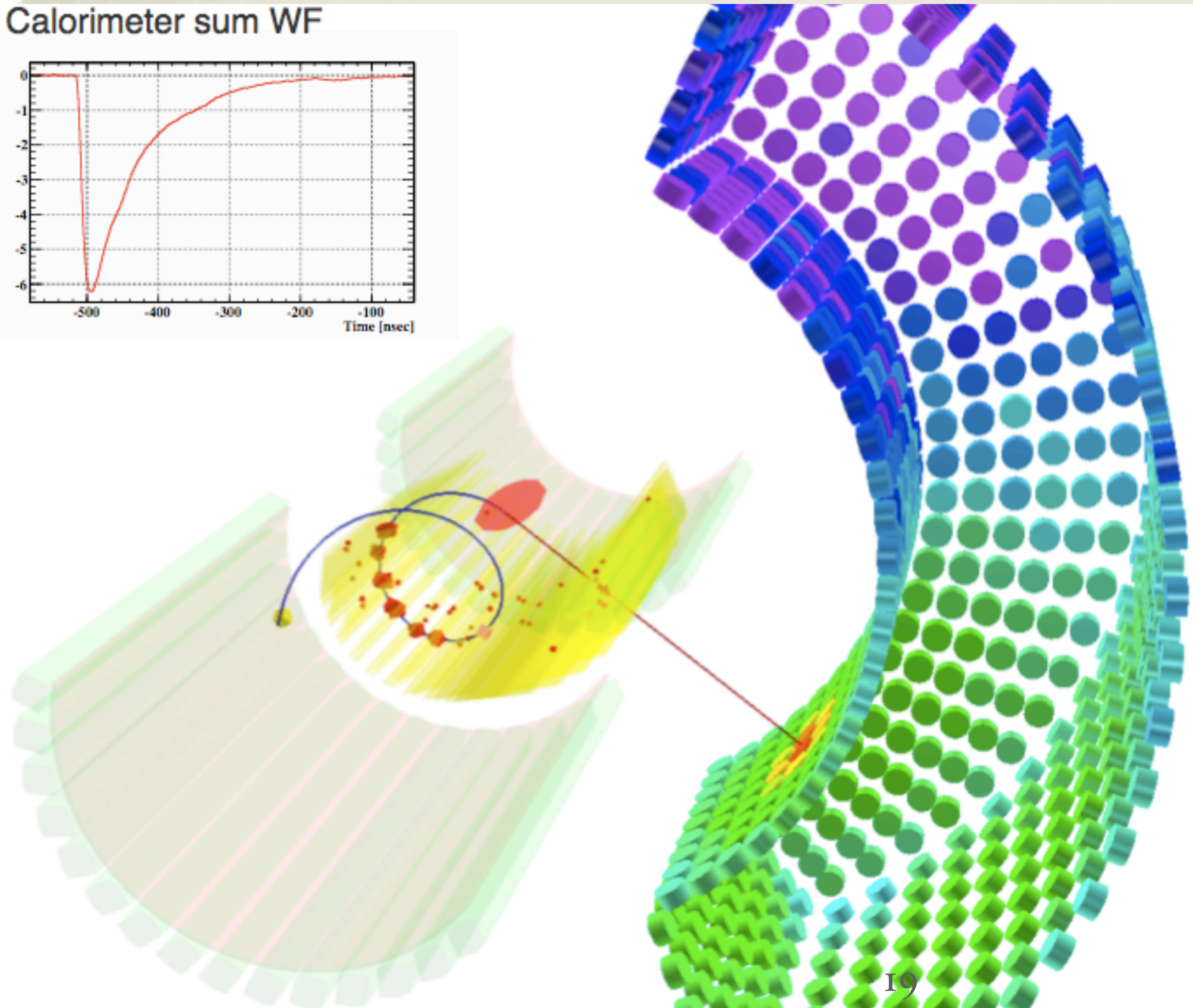
**BR($\mu \rightarrow e\gamma$) @90% C.L. $\leq 1.5 \times 10^{-11}$**

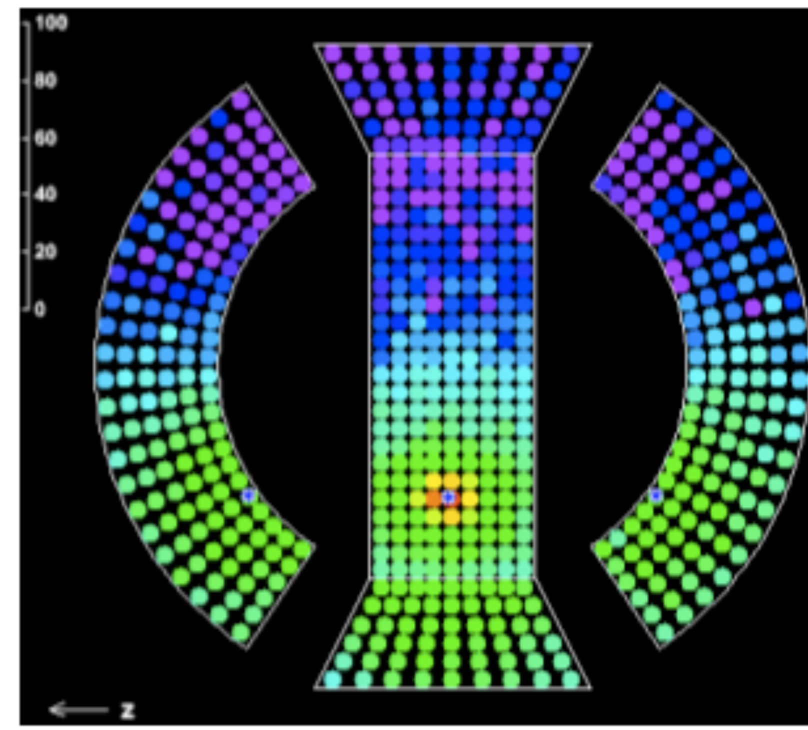


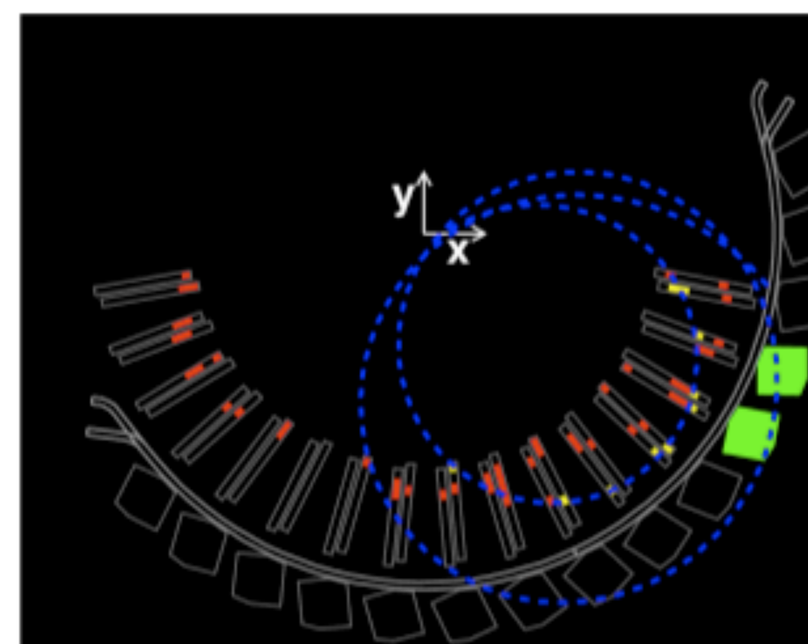
# A candidate event...

- Each highly ranked event was checked carefully

Calorimeter sum WF



# Summary and future prospects

| Variable (in sigma) | 2008 | 2009 | 2010 (preliminary estimate) |
|---|---|---|---|
| Gamma Energy (%) | 2.0 (w>2cm ) | ← | 1.5 (w>2cm ) |
| Gamma Timing (psec) | 80 | > 67 | 68 |
| Gamma Position (mm) | 5 (u,v) - 6 (w) | ← | ← |
| Gamma Efficiency (%) | 63 | 58 | ← |
| Positron Momentum (%) | 1.6 | 0.74 (core) | 0.7 |
| Positron Timing (psec) | <125 | ← | ← |
| Positron Angle (mrad) | 10 (φ) - 18 (ϑ) | 7.4 (φ) - 11.2 (ϑ) | 8 (φ) - 8 (ϑ) |
| Positron Efficiency (%) | 14 | 40 | ← |
| Gamma-Positron Timing (psec) | 148 | 142 (core) | 120 |
| Muon decay point (mm) | 3.2 (R) - 4.5 (Z) | 2.3 (R) - 2.8 (Z) | 1.4 (R) - 2.5 (Z) |
| Trigger efficiency (%) | 66 | 84 | 94 |
| DAQ time/Real time (days) | 48/78 | 35/43 | 95/117 |
| Stopping Muon Rate ($sec^{-1}$) | $3 \times 10^7$ | $2.9 \times 10^7$ | $3 \times 10^7$ |
| Sensitivity | $1.3 \times 10^{-11}$ | $6.1 \times 10^{-12}$ | $2.0 \times 10^{-12}$ |
| B.R. upper limit | $2.8 \times 10^{-11}$ | $1.5 \times 10^{-11}$ | |

# Conclusions

- During the 2009 data taking a sensitivity two time lower than the actual B.R.($\mu \rightarrow e\ \gamma$) limit was reached ($6.1 \times 10^{-12}$)
- A B.R. ($\mu \rightarrow e\ \gamma$) $\leq 1.5 \times 10^{-11}$ was set by using only ~ 1.5 months of data taking
- The MEG experiment has started a long data taking period
- A sensitivity "a few $\times 10^{-13}$" is expected to be reached in the next 3 years of data taking

# Backup slides

# Normalization

- $BR(\mu^+ \to e^+\gamma)$ is calculated by the 90% C.L. normalizing the upper limit in $N_S$ to the Michel positrons (same cuts) assuming $BR(\mu^+ \to e^+\nu_e\overline{\nu}_\mu) \approx 1$

$$N_{e\gamma} = BR(\mu^+ \to e^+\gamma)\cdot k$$

$$k \equiv N_{e\nu\nu} \times \left[\frac{f_S}{f_M}\right] \times \left[\frac{\varepsilon(TRG=0 \mid e^+\gamma)}{\varepsilon(TRG=22 \mid track \cap e^+_m \cap TC)}\right] \times A(\gamma \mid track)\cdot\varepsilon(\gamma)\cdot Psc(22)$$

$$f_S \equiv A(DC)\cdot\varepsilon(track, p_e > 50\text{MeV} \mid DC)\cdot\varepsilon(TC \mid p_e > 50\text{MeV})\big|_S$$

$$f_M \equiv \ldots\big|_M$$

Signal to Michel relative efficiency (data/MC)

TRG = 0 : MEG Trigger
TRG =22: Special Trigger fo Michel positrons

Prescaling factor = $10^7$

**$k = 1.0 \times 10^{12}$ (+- 10%)**